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A Site-specific Study of In-building Wireless Solutions

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Abstract—This paper studies the different ways of extending wireless coverage for high data rates and improving the data capacity in a building. The solutions considered include deployments of single or multiple small base stations, i.e. Picocell or Femtocell, and distributed antenna system, operated on the same frequency as the macro cellular network. We look at the radio performance of each solution in a LTE downlink context with in-building path loss values retrieved from real-life measurements. The performance is compared by means of maximum supportable user numbers and average system throughput. Potential gains by hard frequency reuse in the building and QoS based packet scheduling are examined. Simulation results show the robustness of the proposed distributed antenna system and the conditions for multi-Femtocell deployment.

Keywords- *site-specific, in-building wireless, Femtocell, distributed antenna system*

I. INTRODUCTION

Network congestion often occurs inside buildings where the local traffic need exceeds the capacity offered by the conventional outdoor macro sites, causing low service quality or call drops. Such places, the so-called indoor hotspots, can be office buildings during working hours, shopping malls or other enterprise buildings with a high ‘mobile population’ density.

It is an increasing challenge for operators to deliver high-quality inbuilding wireless (IBW) services with current macro cellular network infrastructures. The reasons reside in, firstly, the inadequacy of indoor radio coverage by outdoor base stations due to large and varied penetration loss through walls, and the fast evolution of indoor data traffic requirements. It is expected that some 70%-80% mobile traffic will be generated inside buildings [1]. The fast traffic growth is not only driven by an increasing number of data service subscribers, but also because of the high data rate demand per subscriber.

This problem can be solved by providing additional capacity locally to the hotspot by installing a dedicated system inside the building. In this setup the wall penetration loss provides isolation between the outdoor macro cellular layer and the indoor radio system. There exist several alternatives for such a deployment: single or multiple small base stations and distributed antenna systems (DAS). The term small base stations (BS) refers herein to Picocell and Femtocell access points. The distributed radio element is called an access point (AP) to describe the source of the signal in downlink regardless of whether it is a Femto access point or a DAS antenna. The

Femto, Pico or DAS prefixes define the logical type of cell. Picocell APs work much like a macro base station, except for lower transmission power. Femtocell APs, by the definition of the Femto Forum [17], are low-power wireless access points which connect to the core network using residential DSL or cable broadband connections. Current Femtocell APs, or Femtocells for short, are suited for residential deployment, with lower power than a Picocell, and restricted to up to 4 connected data subscribers [12]. However, it is expected that the office Femto targeting the small and medium enterprise market, will lead to products with higher RF power and support for a relatively large number of simultaneous users [13]. Despite the different backhaul solution they use, there should be no difference between an office Femto and a Picocell from the radio performance point of view, providing they operate at the same power level and serve the same group of users. We will treat these two concepts identically and collectively call them Femto in the rest of the paper.

Research concerning in-building deployment of Femtos focus mainly on the co-existence issue of macro cell and co-channel Femtos [2]-[4]. Another focus lies in inter-Femto interference optimization in dense residential deployment cases providing random user placement of Femtos [5]-[7]. In this study, we compare the LTE downlink (DL) performance of a number of solutions for IBW service which are capable of handling simultaneously a large number of users, with or without the need for coordinated Pico/Femto placement. In LTE, the orthogonal frequency division multiplexing access (OFDMA) is used as the multiple access technique. The flexibility of sub-carrier assignment in the LTE system makes it possible for LTE Femtos to have more efficient interference reduction properties. For the case without planning, we propose an intelligent DAS solution. Conventional DAS systems were initially studied in [8], and the benefits of more advanced systems have been studied in e.g. [9] and [10]. In our proposed solution we make intelligent decisions on the source of interferer and commit coordinated interference avoidance scheduling. The performance study takes into account the interference from co-channel macro cells under full load. We consider only the IBW user experience and neglect the potential impact on the outdoor users.

The rest of the paper is organized as follows. In section II, we introduce the studied solutions for IBW, i.e. Femto and DAS. We also discuss some common issues frequently encountered in an IBW deployment scenario and explain our choices on this. We describe our simulation assumptions and present simulation results in section IV and V, respectively. The conclusions are drawn in section VI.

II. INDOOR COVERAGE SOLUTIONS

Different techniques are available to extend indoor coverage from indoor base stations. Among those, the most common ones are Femto and DAS based solutions. Distributed antenna systems consist of distributed remote antennas connected to a central controller by cable or fiber-optic. The remote antennas, or remote APs, jointly extend the spatial coverage, but add no extra capacity to the system. We call this DAS a conventional DAS. Later, we propose an intelligent DAS feature where extra capacity is obtained by reuse of the frequency resources.

A. Femto

Femtos are in general stand-alone APs with little or no information exchange between them, and hence mostly commit uncoordinated packet scheduling.

In the enterprise building solution, the placement of the Femto APs is usually planned rather than randomly placed.

B. Conventional DAS (C-DAS)

In a conventional DAS all distributed elements are connected to one or more centrally located base stations. The output signals from each base station are sent to all remote elements in a broadcasting manner, i.e. the DL transmission at each remote AP is the same. The remote APs shorten the access distance to mobile user equipments (UE), thus help in extending the coverage area. However, because of the broadcast operation there is no frequency reuse within the system, hence, when the number of APs becomes sufficiently large for good coverage, the system capacity will saturate, and there will be no gain from deploying more APs.

C. Intelligent DAS (I-DAS)

A way of further increasing DAS capacity is the possibility to reuse available frequency resources, i.e. between remote APs. In the I-DAS concept each remote element is identifiable at the central controller as a single cell. This allows a centralized coordination of AP transmission and scheduling decisions to be made jointly at the central controller for all cells.

In the DL the average path loss values to nearby APs can be estimated by the user using reference signals transmitted from individual APs. The path loss estimation can then be used for both cell selection and coordinated transmission: The user chooses the cell with the smallest path loss value, and then it makes a comparison between the serving cell path loss and other cell path loss values; if it is found that the path loss value difference from another cell is less than a (interference) threshold, the cell is recognized as a strong interferer. In joint scheduling, the interfering cell will be prohibited from transmitting on the same physical resources as was already assigned to the interfered user. In this way, the interference from a set of strong interferers, determined by the interference threshold, will be eliminated. The price of the reduced interference is less frequency reuse.

The three solutions which we study in this paper can be summarized by how the system bandwidth (BW) is shared and where the interference originates in Tab. I.

TABLE I. STUDIED IBW SOLUTIONS

Solution	System configure	Interference source
C-DAS	Single-cell with BW sharing between APs	Macro layer
Femto	Multi-cell: with BW sharing per AP	Macro layer and other APs

I-DAS	Multi-cell with partial BW sharing per AP, depending on interference threshold	Macro layer and other APs (depending on interference threshold)
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D. Deployment Issues: Access point placement

Previous studies in [11] investigated the impact of base station placement on IBW system capacity performance. For multi-floor buildings two configurations were evaluated: an aligned placement where BSs on different floors are vertically aligned at the same position and an offset placement where BSs on different floors are placed interleaved to each other. We adopt both configurations in our study. An example of a 6 AP aligned (on the left side) and offset (on the right side) placement along with the site-specific building floor plan used in this study is illustrated in Fig. 1. The circular markers represent the AP positions, while different colors stand for orthogonal frequency sub-bands employed by each AP with frequency reuse 2. In reuse 1, all APs use the same frequency sub-bands.

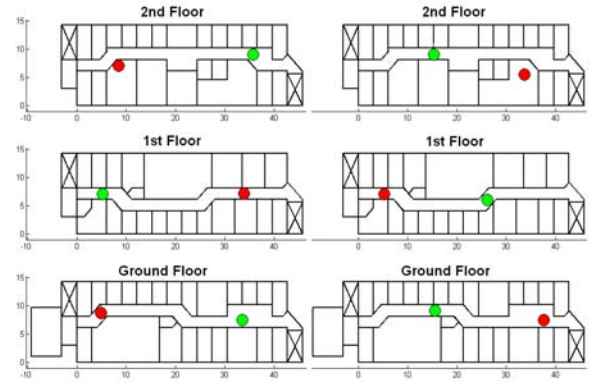


Figure 1. Site-specific floor plan and 6 AP placement.

III. SIMULATION ASSUMPTIONS

A. Site-specific Settings

The site-specific building in Fig. 1 is a 3-floor office building with overall dimensions 15 meters wide and 50 meters long. The building is located in a macro environment with the building facing directly to the main beam of one sector of the nearest BS at a distance of 167 meters. The average interference signal level is around -89 dBm inside the building, with the side facing the main beam at an approximately 9dB higher interference level than the opposite side.

B. Path loss and Shadowing

All path loss values have been collected from a measurement calibrated path loss model of the building shown in Fig. 1 [14]. The model has a standard prediction error as low as 3 to 4 dB.

The path loss values account for most of the correlated shadowing effect caused by building structure and furnishings. The unaccounted random part follows closely a log-normal distributed variable and has been accounted for in the simulations by adding an i.i.d. lognormal variation with 3 dB standard deviation to every predicted path loss value.

C. Other simulation assumptions

The parameters for macro sites, except for the pathloss model, and LTE related parameters as well as the sub-carrier modeling in OFDM are adopted from [16]. The users are uniformly distributed in the building with full buffer traffic. The transmitting power is 23 dBm for every AP. The system is

a SISO system. The outage level is set to be 5% and the expected outage user throughput target is 1.5 Mbps.

In the simulation we assume that the channel is flat over the 10 MHz system bandwidth. A link to system mapping is adopted from [15], to approximate the equivalent system level throughput in an LTE downlink system from calculated signal to interference plus noise ratio (SINR) values. The parameters for the mapping are selected as in a round robin (RR), SISO system in [15].

D. Packet Scheduling

We assume that there is no specific time domain packet scheduling in our simulation, that is, all the users are scheduled in the frequency domain packet scheduling (FDPS) for allocating frequency resources each transmission time interval (TTI). We adjust our schemes in order to achieve different service types to the IBW users. FDPS assigns physical resource blocks (PRB) to users according to various strategies. The scheduling in our simulation is non-frequency selective in the sense that at the transmitter side only wide-band measurements are available.

1) Best effort (BE)

In this scheme the scheduler of each cell tries to assign an equal amount of frequency resources to each of its users. The received quality of service in terms of user throughput for each user depends totally on its SINR condition and the number of active users of its serving cell.

2) Quality guaranteed (QG)

The quality guaranteed FDPS provides protection to low SINR users and upgrade their individual throughput by allocating more frequency resources to these users and restrict the allocation for users with high SINR. Before the PRB assignment, the scheduler makes use of the wideband SINR measurement and calculates for each user the number of PRBs it needs to achieve the user throughput target. Then the scheduler assigns randomly the required number of PRBs over the 10 MHz system bandwidth. The procedure starts from the user with lowest RB request to the user with highest RB request until there is no RB left or all the users belonging to the cell are assigned.

If all cell users are successfully assigned, the QG scheduler checks whether there are PRBs left unassigned. If so, the scheduler distributes the unassigned PRBs equally among all cell users, as in the lower part of Fig. 2. We refer to this QG algorithm as full-load QG, or QG in short form, reflecting that it assigns the whole system bandwidth for DL transmission.

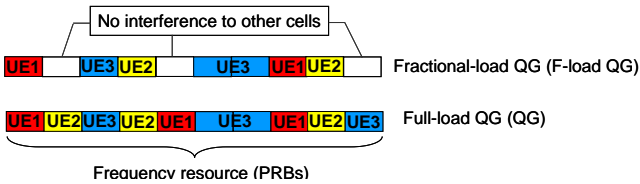


Figure 2. Example of QG and F-load QG FDPS in one cell.

However, due to the uneven load of different cells, there will be users assigned with a larger amount of PRBs in a light-loaded cell than they actually need to achieve the target data rate. These aggressive users eat up unnecessary resource and generate additional interference to other users. To aim at a constant data rate of 1.5 Mbps, i.e. to provide streaming-like service, we introduce the so called fractional-load (F-load) QG FDPS. This scheme reduces the interference level from one cell

to the others and saves room for accommodating more users in the whole system.

The F-load QG FDPS operation keeps the PRBs remaining after the first step of the QG algorithm unassigned (upper part of Fig. 2). Those random PRBs from each cell will generate no interference to other cells, and introduce random interference reduction in the multi-Femto deployment.

IV. SIMULATION RESULTS

In the evaluation of the IBW solutions we use two metrics: 1) the number of users which can be supported in the system and 2) the average total system throughput. The former defines the maximum simultaneous number of users that can be handled by the IBW system, under the constraint that 95% of them achieve equal to or higher than the predefined outage user throughput target of 1.5 Mbps. The single AP performance, located in the middle of the building is taken as a reference and shown on the left in Fig. 3-9. The I-DAS interference threshold determines the allowable inter-cell interference level in I-DAS systems, and is set to be 3dB, 6dB and 10dB, respectively in the simulations. However, we only show results for 10dB since this setting leads to the best performance.

In Fig. 3, 4, 7 and 8, the solid color represents results for aligned placement of APs (denoted by capital 'A') and the dashed and faded color represents results for offset placement (denoted by capital 'O').

A. Best-effort Results

Figure 3 and 4 show the supported user number capacity performance of BE FDPS with hard frequency reuse 1 and reuse 2, respectively.

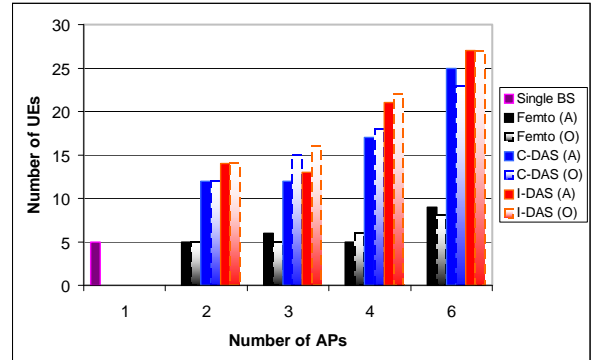


Figure 3. Supported number of users for BE in reuse 1, as a function of the number of APs.

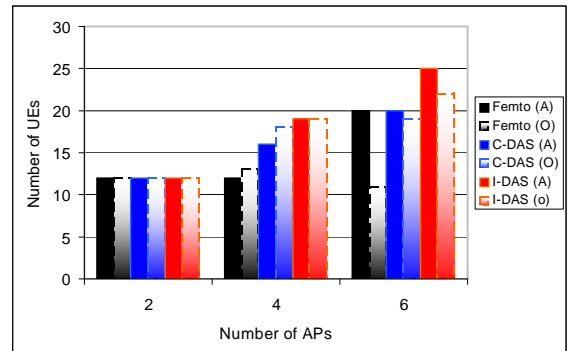


Figure 4. Supported number of users for BE in reuse 2, as a function of the number of APs

Both the supported user number capacity of C-DAS and I-DAS increases as the number of AP increases. This is due to the improved average user SINR condition for C-DAS and the combined effect of user SINR condition and effective frequency reuse for I-DAS. However, both experience a reduction in frequency reuse 2 compared to the same AP configuration in reuse 1 due to the reduction in available frequency resources per AP. The coordinated multi-cell system I-DAS gives the best supported user number capacity performance for all AP configurations.

The distinctive performance is given by multi-Femto system, which is an uncoordinated system from the radio management point of view. Its supported user number capacity performance fluctuates around the performance of a single base station system when the number of Femtos is less than 6. With 6 Femtos deployed in the system, the performance is slightly improved. However, by using hard-frequency reuse 2, the multi-Femto system is better protected from inter-Femto interference. It is seen possible to achieve a relatively high supported user number capacity performance, especially in dense deployment, i.e. 6 Femtos. Another factor which is critical to Femto performance in reuse 2 scenarios is the Femto placement. With an offset placement the maximum supported number of users achieves only about half of the aligned placement. Contrary to Femto, the DAS solution is more robust to a non-perfect placement. In terms of supported user number capacity performance in this best effort service, the advantage of C-DAS and I-DAS over multi-Femto is clearly visible.

We then take a look at the average system throughput, which is shown in Fig. 5. In Fig. 5 and 9, the solid color represents hard frequency reuse 1, the dashed and faded color represents reuse 2, denoted as ‘Reuse 1’ and ‘Reuse 2’.

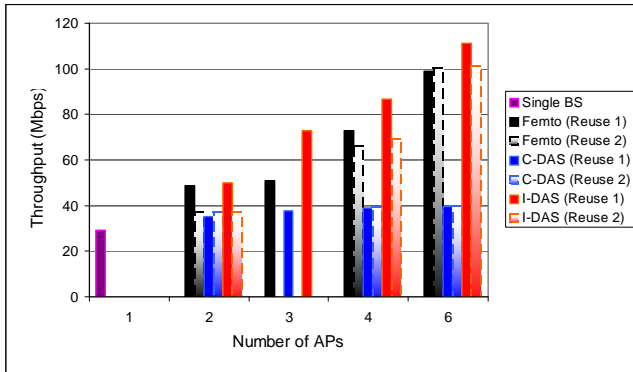


Figure 5. Average system throughput for BE, as a function of the number of APs.

The best system throughput performance is achieved by I-DAS. For the other two systems, despite the poor results in Fig. 3, the multi-Femto system achieves much higher system throughput than the C-DAS system in this setting. As a single cell system, C-DAS reaches almost the peak system throughput with 4 APs. There is only marginal gain by inserting more APs. In the multi-Femto system, users that have high SINR conditions benefit a lot from the increased shared frequency resource and contribute substantially to the high system throughput. However, when a new Femto is added into the system, a lot of users will be exposed to more severe interference. Although the frequency resource shared by each user is increased, the supported user number capacity performance is not improved much.

B. Quality-guaranteed Results

The problem with Femtos is that the user throughput is dominated by its SINR condition. A lot of users are suffering from heavy inter-Femto interference. At the same time a lot of users in the close vicinity of a Femto enjoy very high throughput. We can take advantage of Femto systems' high overall throughput if we balance the user throughput by the quality guaranteed FDPS. The results will be shown in the next section.

The QG FDPS is potentially most beneficial to multi-Femto systems in the sense that it balances the user throughput: it assigns users in poor SINR conditions with more frequency resources and users in good SINR conditions with less resources. The maximum supported number of users of QG FDPS is shown in Fig. 6 and 7, and the average system throughput results in Fig. 8.

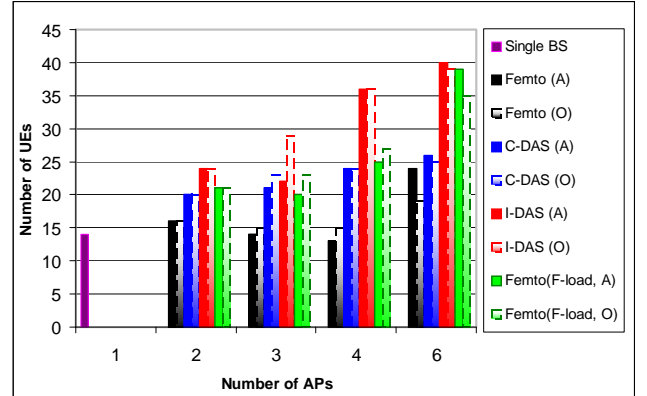


Figure 6. Supported number of users for QG in reuse 1, as a function of the number of APs

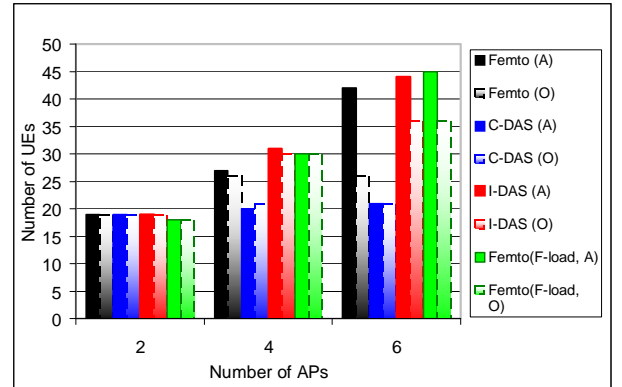


Figure 7. Supported number of users for QG in reuse 2, as a function of the number of APs

The QG FDPS improves the maximum number of supported users for all systems. There is an average gain of over 50% for I-DAS system and more than doubled for multi-Femto system, and is more obvious for a large number of APs. The benefit for C-DAS exists especially for a small number of APs. In frequency reuse 2 scenarios, multi-Femto outperforms C-DAS and achieves comparable supported user number capacity performance to I-DAS.

Fractional load QG multi-Femto systems achieve similar performance to I-DAS in most scenarios and even slightly outperform I-DAS in reuse 2 with 6 APs. There is an obvious gain of F-load Femtos over full load Femtos in reuse 1 scenarios. The advantage of fractional load Femtos also resides

in its robustness towards a non-optimized placement, i.e. with 6 APs in reuse 2 in Fig. 7.

The drawback of this fractional load system is presented in Fig. 8. That is, it suffers from 15% to 40% reduction in average system throughput, because, although the partial frequency usage improves the SINR condition, this upgrade is insufficient to compensate for the loss of throughput for users with high SINR.

Compared to BE FDPS, the average system throughput is decreased. Overall, however, the decrease is relatively small if compared to the increase in the number of supported users: There is 10% loss in the worst case for both I-DAS and multi-Femto system while the gain in number of users is more than 50%.

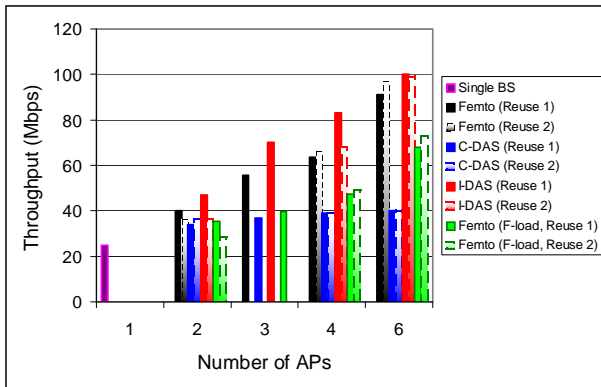


Figure 8. Average system throughput for QG, as a function of the number of APs.

When there is no macro interference, i.e. macro layer is deployed in an adjacent channel, the supported number of users in C-DAS reaches the maximum of 26 regardless of the number of APs, i.e. a single base station (1 AP C-DAS) performs as good as 6 AP C-DAS. So does the average system throughput of C-DAS. The increase of system throughput for Femto and I-DAS systems decreases from 10% to less than 1% as the number of APs grows from 2 to 6. The same trend is witnessed also in the number of supported users. Without macro interference, as long as the indoor signal can suppress the noise power in the whole building, i.e. by 24.5dB where the highest spectrum efficiency can be achieved, there is no need to further increase the numbers of APs in a single cell system (C-DAS). Also, when the number of APs is sufficient to combat the macro interference, i.e. more than 4 APs in our study, the performance will not be much affected by macro interference.

V. CONCLUSIONS

In this study different IBW solutions are simulated and evaluated with two distinct FDPS schemes. Based on our observations, the proposed I-DAS system gives the best performance in almost all scenarios in terms of maximum supported user number under outage throughput constraints and overall system performance. The performance of C-DAS saturates when there are enough of remote antennas to have a good coverage. Its supported user number is better than Femto system only in reuse 1 scenarios, and its system throughput is always lower than multi-Femto system with the same AP number. The performance of a multi-Femto system suffers to a

large extent from inter-cell interference when all Femtos reuse the same frequency resource. By using hard frequency reuse 2, multi-Femto systems can potentially be a good solution to achieve good radio performance. However, in order to achieve similar performance to I-DAS, a careful radio planning is needed for the deployment of multiple Femtos with frequency reuse 2. Another way to improve multi-Femto performance in terms of supported user number under the outage throughput constraint is by using fractional load QG FDPS. The F-load QG multi-Femto systems can achieve comparable or even slightly better performance than I-DAS on supported user number, but suffers from a reduced average system throughput by about 20 to 40 percent.

Overall, QG FDPS is preferred to BE FDPS in the IBW solution, which can largely improve the supported user number capacity performance, with comparatively small sacrifice in the system throughput.

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